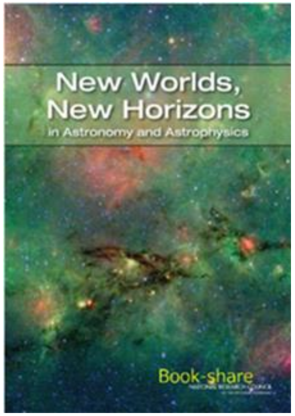
Overview and Recent Accomplishments of Advanced Mirror Technology Development Phase 2 (AMTD-2)

H. Philip Stahl, MSFC

AMTD is a funded NASA Strategic Astrophysics Technology (SAT) project

SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2015

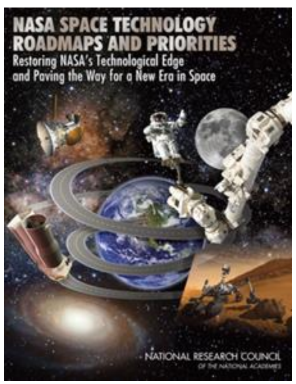
Future UVOIR Space Telescopes require Mirror Technology



Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

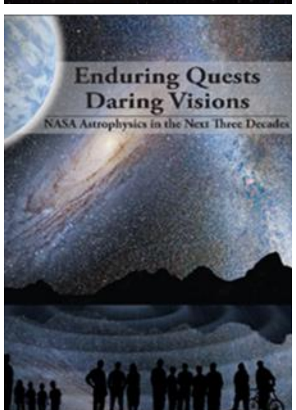
Exoplanet Mission (New-Worlds Explorer)

UVOIR Space Telescope (4 meter or larger)



2012 NASA Space Technology Roadmaps & Priorities: Top Technical Challenge C2 recommended:

New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects …



2014 Enduring Quests Daring Visions recommended:

8 to 16-m LUVOIR Surveyor with sensitivity and angular resolution to "dramatically enhance detection of Earth-sized planets to statistically significant numbers, and allow in-depth spectroscopic characterization."

Objective

AMTD's objective is to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

AMTD is not developing technology for a specific mission.

Potential high-contrast imaging & spectroscopy architectures:

single aperture monolithic mirror telescope,

single aperture segmented mirror telescope,

sparse aperture, and

interferometers.

Multiple Technology Paths

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide the science community with options, we are pursuing multiple technology paths for both monolithic and segmented aperture telescopes.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

Very Smooth Surfaces	< 10 nm rms
Thermal Stability	Low CTE Material
Mechanical Stability	High Stiffness Mirror Substrates

Technical Approach/Methodology

To accomplish our objective, we:

- Use a science-driven systems engineering approach.
- Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

Mature Technology Simultaneous because all are required to make a primary mirror assembly (PMA); AND, it is the PMA's on-orbit performance which determines science return.

PMA stiffness depends on substrate and support stiffness.

Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.

On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.

Segment-to-segment phasing depends on substrate & structure stiffness.

Phase 1 & 2

Goals, Objectives & Tasks

Goals

To accomplish Objective, must mature 6 linked technologies:

Large-Aperture, Low Areal Density, High Stiffness Mirrors: 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.

Support System: Large-aperture mirrors require large support systems to ensure that they survive launch & deploy on orbit in a stress-free & undistorted shape.

Mid/High Spatial Frequency Figure Error: A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.

Segment Edges: Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.

Segment-to-Segment Gap Phasing: Segment phasing is critical for producing a high-quality temporally stable PSF.

Integrated Model Validation: On-orbit performance is determined by mechanical & thermal stability. Future systems require validated models.

Phase 1: Goals, Progress & Accomplishments

Key
- Done
- Stopped
- In-Process
- Not Started Yet

Systems Engineering:

- **derive from science requirements monolithic mirror specifications**
- **derive from science requirements segmented mirror specifications**

Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:

- **make a subsection mirror via a process traceable to 500 mm deep mirrors**

Support System:

- **produce pre-Phase-A point designs for candidate primary mirror architectures;**
- **demonstrate specific actuation and vibration isolation mechanisms**

Mid/High Spatial Frequency Figure Error:

- **'null' polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2°C operational temperature.**

Segment Edges:

- **demonstrate an achromatic edge apodization mask**

Segment to Segment Gap Phasing:

- **develop models for segmented primary mirror performance; and**
- **test prototype passive & active mechanisms to control gaps to ~ 1 nm rms.**

Integrated Model Validation:

- **validate thermal model by testing the AMSD and deep core mirrors at 2°C**
- **validate mechanical models by static load test.**

Phase 1: Key Accomplishments

- Derived from Science Requirements, Specifications for Primary Mirror Wavefront Error and Stability
  - Surface < 10 nm rms (low ~5 nm, mid ~5 nm, high ~3 nm)
  - Stability < 10 picometers rms per 10 minutes
- Demonstrated, at the 0.5-m scale, the ability to make mechanically stiff, i.e. stable, UVOIR traceable mirrors:
  - <6 nm rms surface
  - 60-kg/m2
  - 400-mm deep-core substrate

using the stack-core low-temperature-fusion/low-temperature-slumping (LTF/LTS) process.

- Developed Tools for Integrated Modeling & Verification

Phase 2: Tasks

Refine engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 4 inter-linked critical technologies.

Large-Aperture, Low Areal Density, High Stiffness Mirrors

Fabricate a 1/3rd scale model of a 4-m class 400 mm thick deep-core ULE© mirror – to demo lateral scaling.

Support System **– continue Phase A design studies**

Mid/High Spatial Frequency Figure Error

Test 1/3rd scale ULE© & 1.2 m Zerodur Schott mirror at 280K

Integrated Model Validation **– continue developing and validating tools**

Phase 2: Tasks

Key
- **Done**
- **Stopped**
- **In-Process**
- Not Started Yet

Monolithic Mirror Substrate Technology
- Fabricate and test A-Basis allowable required for mirror
- Design 1/3-scale model of a 4-m x 400-mm class ~150Hz ULE® mirror
- Design support structure for Zerodur 1.2m mirror

Mirror Preparation
- Fabricate & polish 1/3-scale model ULE mirror & support structure
- Fabricate support structure & Polish Zerodur mirror

Thermal Characterization
- "Qualify" (i.e., test) two candidate lightweight primary mirrors (1.35m or 1.5m Harris & 1.2m Zerodur Schott) in X-Ray & Cryogenic Facility at MSFC
  - Characterize their optical performance from 250K to ambient

Expose to representative vibration and acoustic launch environments & conduct modal test of both mirrors

Engineering Specifications

Next Presentation

Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates

Thursday in ITAR Mirror Technology Session:

1:20 pm, Egerman, AMTD-2 UVOIR Mirror Design and Fabrication Status

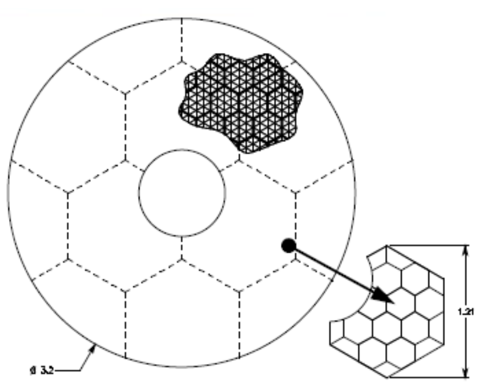
Large Stable Mirror Substrates

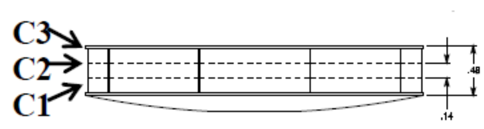
Future large-aperture space telescopes (regardless of monolithic or segmented) need ultra-stable mechanical and thermal performance for high-contrast imaging.

This requires larger, thicker, and stiffer substrates.

Phase 1 demonstrated stacked core low-temperature fusion process to cost effectively make mirrors thicker than 300 mm by making a 40 cm ‘cut-out’ of a 4-m mirror.

Phase 2 designing a 1.5 m subscale of a 4-m mirror to demonstrate lateral scalability of stacked core process.



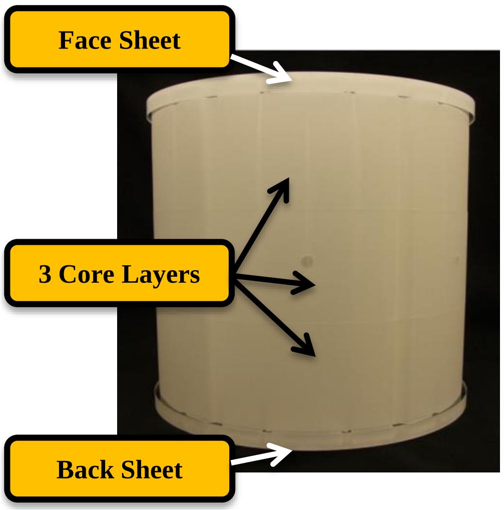


4m PM Conceptual Layout

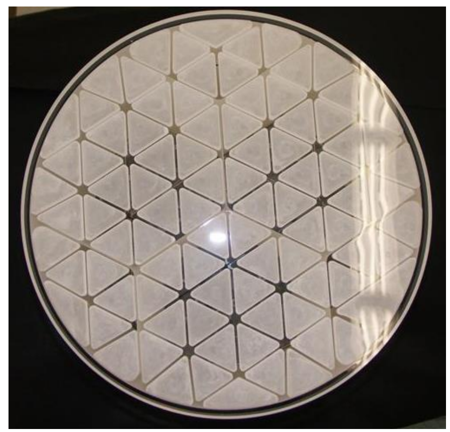
43 cm Deep Core Mirror

Harris successfully demonstrated 5-layer ‘stack & fuse’ technique which fuses 3 core structural element layers to front & back faceplates.

Made 43 cm ‘cut-out’ of a 4 m dia, > 0.4 m deep, 60 kg/m^2 mirror substrate.



Post-Fusion Side View
3 Core Layers and Vent Hole Visible



Post-Fusion Top View
Pocket Milled Faceplate

Post Slump:
2.5 meter Radius of Curvature

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

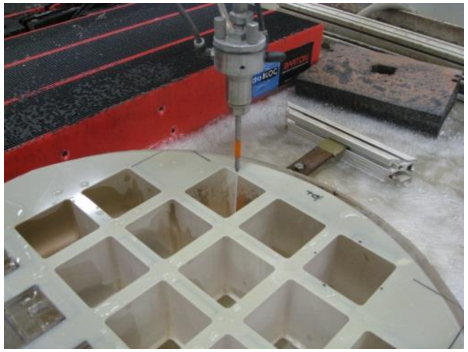
Strength Testing

AMTD-1: Harris strength tested the core to core LTF bond strength on 12 Modulus of Rupture (MOR) test articles.

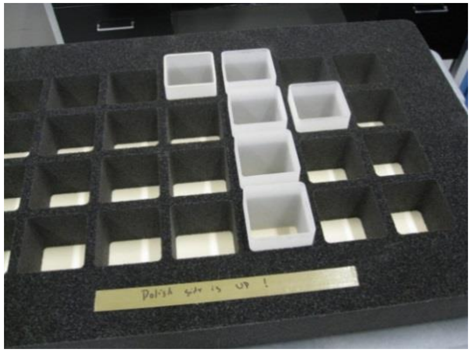
- Weibull 99% survival value was 15% above conservative design allowable. Data ranged from 30% to 200% above design allowable.

AMTD-2: A-Basis test of core rib to core rib LTF bond strength.

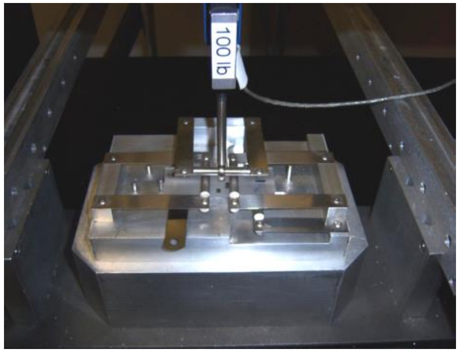
- 60+ MOR Samples: 30+ samples aligned; 30+ core misaligned
- A-basis Weibull 99% confidence strength allowable for 49 samples is 17.5MPa; ~50% higher than the strength of core-to-plate LTF bonds.



MOR Boxes in Abrasive Water Jet (AWJ)



post AWJ, pre-LTF assembly

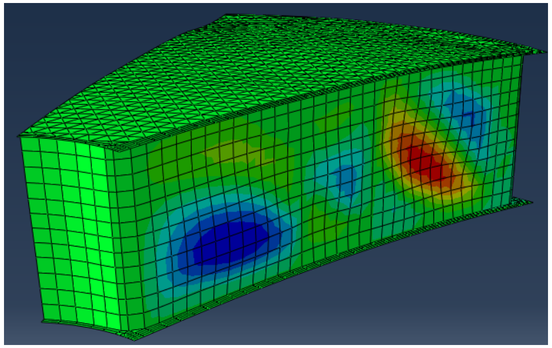


MOR sample in Test Fixture

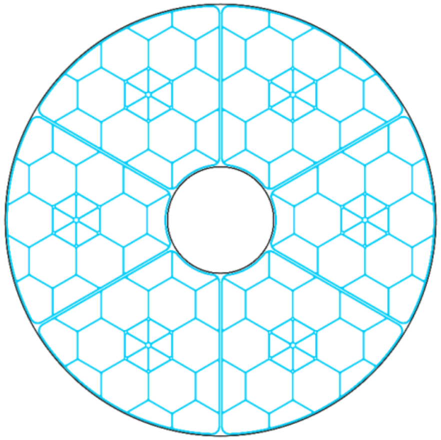
Phase 2: Demonstrates Lateral Scaling

Demonstrate lateral scaling of 'stacked-core' to larger diameter

- Approximately 1/3rd scale model of a 4 meter mirror
  - 1.5m class diameter and about 200mm thick
  - (2) ULE® face plates
  - (3) ULE® glass boules
  - On-axis



Non-linear visco-elastic tools and methods used to design 4-m class mirror, then scaled to 1.5-m

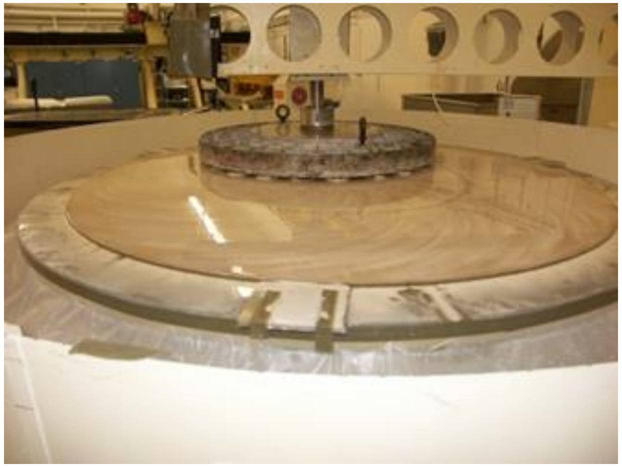


Courtesy: Harris

Completed: design for ~1/3 scale mirror blank of 4m class UVOIR Primary Mirror with solid facesheets.

Phase 2: Fabrication Status

The Face-plates have been cut to size and are being polished.



Water jet cutting of the 18 core elements will start in September.

Integrated Design Tools:

Arnold Mirror Modeler: Arnold Presentation
Thermal Modeling: Brooks Presentation
Dynamic Modeling
and
Model Validation: Eng Presentatino

Support System

Technical Challenge:

- Large-aperture mirrors require large support systems to survive launch & deploy on orbit in a stress-free and undistorted shape.

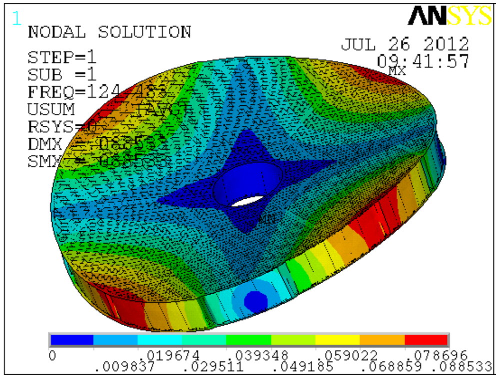
Accomplishments:

- Developed a new modeler tool for ANSYS which can produce 400,000-element models in minutes.
- Tool facilitates transfer of high-resolution mesh to mechanical & thermal analysis tools.
- Used our new tool to compare pre-Phase-A point designs for 4-meter and 8-meter monolithic primary mirror substrates and supports.

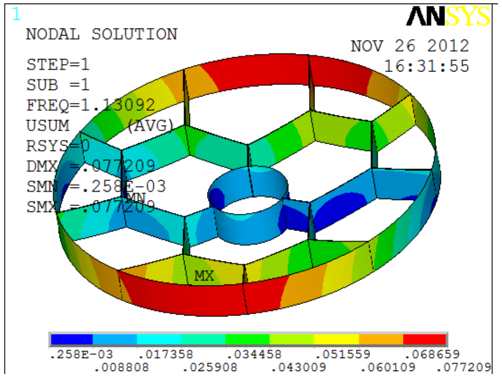
Design Tools and Point Designs

AMTD has developed a powerful tool which quickly creates monolithic or segmented mirror designs; and analyzes their static & dynamic mechanical and thermal performance.

Point Designs: AMTD has used these tools to generate Pre-Phase-A point designs for 4 & 8-m mirror substrates.



Free-Free 1st Mode: 4 m dia 40 cm thick substrate



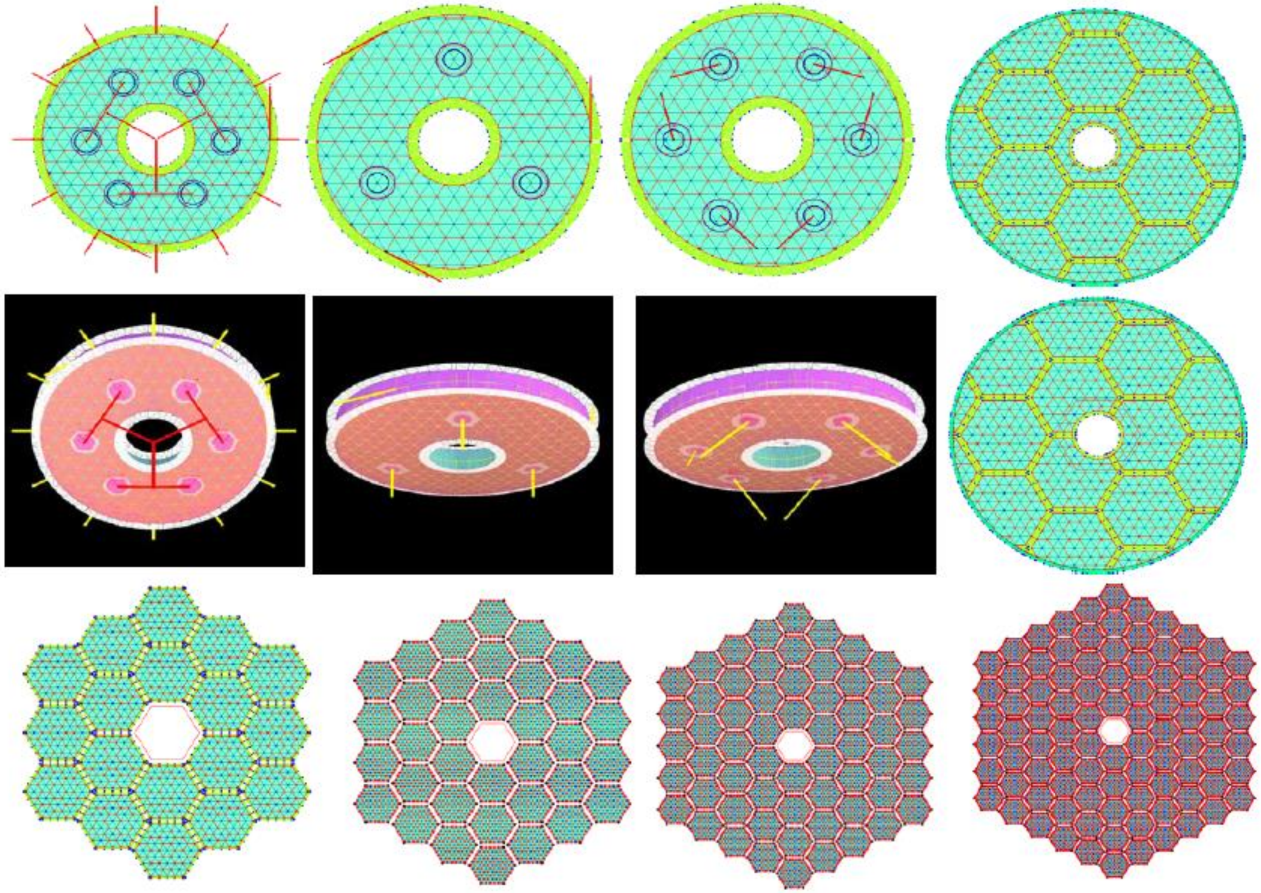
Internal Stress: 4 m dia with 6 support pads

Support System: AMTD has used these tools to generate Pre-Phase-A point designs for 4-m mirror substrate with a launch support system.

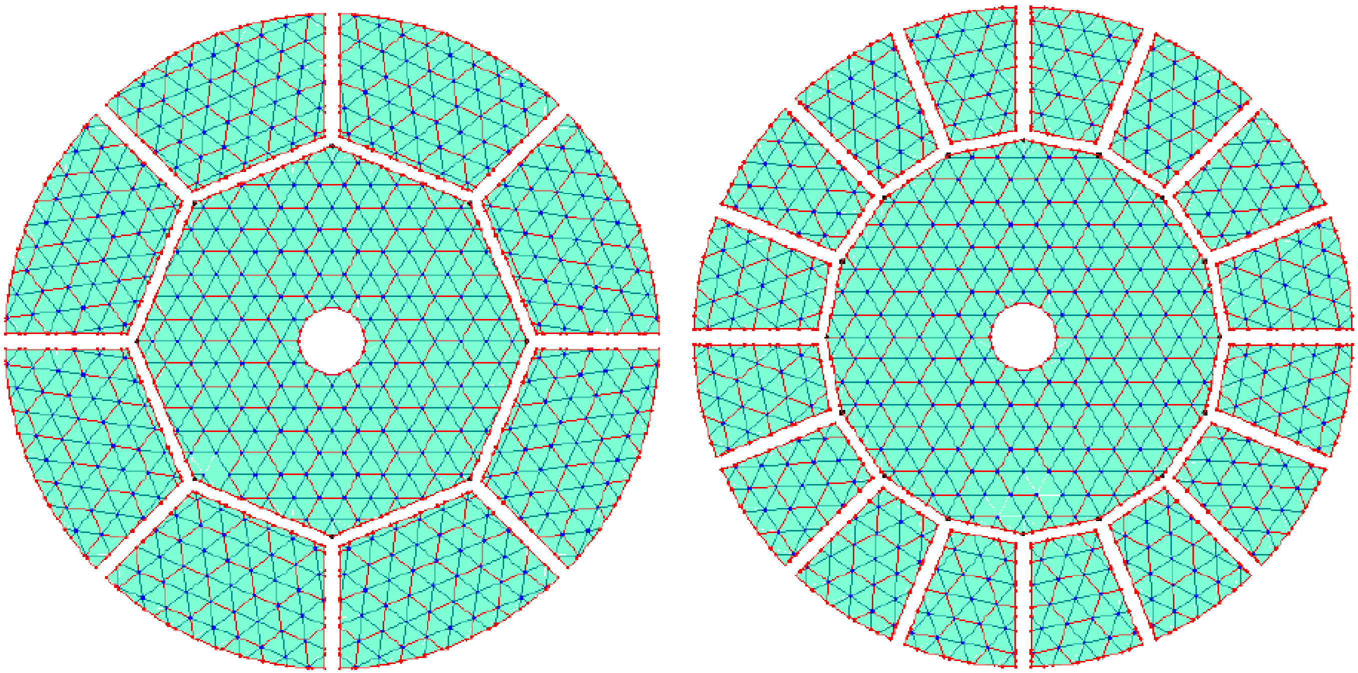
TELEDYNE BROWN ENGINEERING

a.i. solutions

TYPES OF MODELS GENERATED

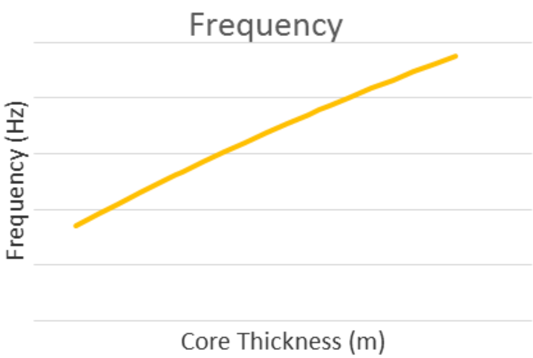


COMBINING PETALS WITH MONOLITH



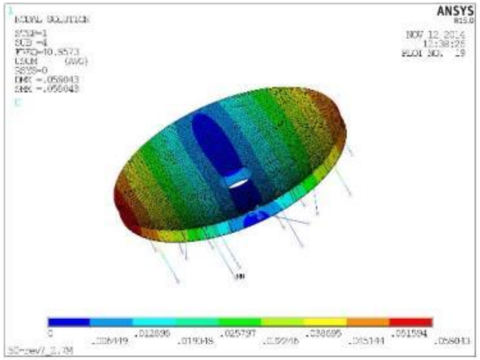
One option for limited shroud diameter is to have as large a central monolith as possible, with deployable petals. This provides a better diffraction pattern than uniform segment patterns, as well as more mission flexibility.

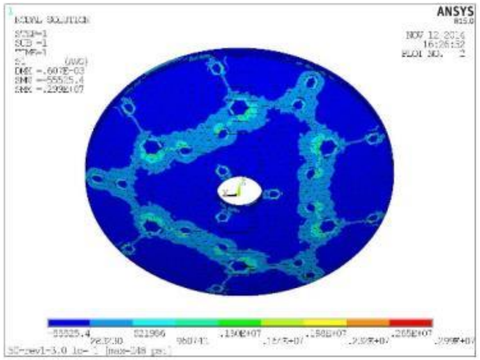
75 Hz and 50 Hz 4-m Diameter Design Points



75 Hz:
170 mm thick
820.8 kg

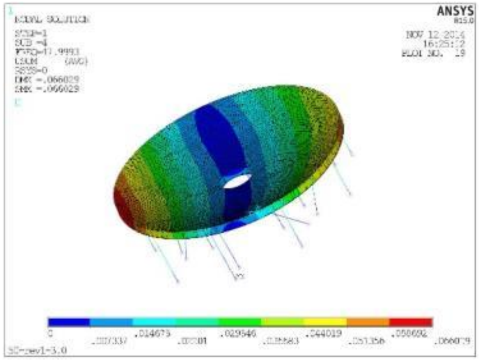
21 supports,
244 psi

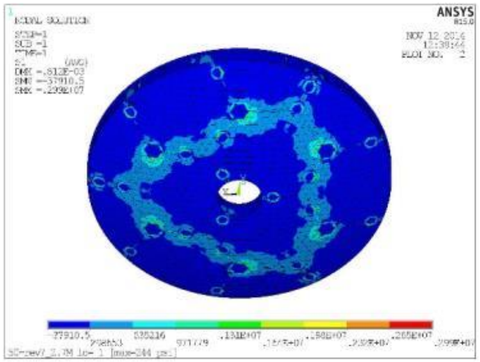




50 Hz:
80 mm thick
727.0 kg

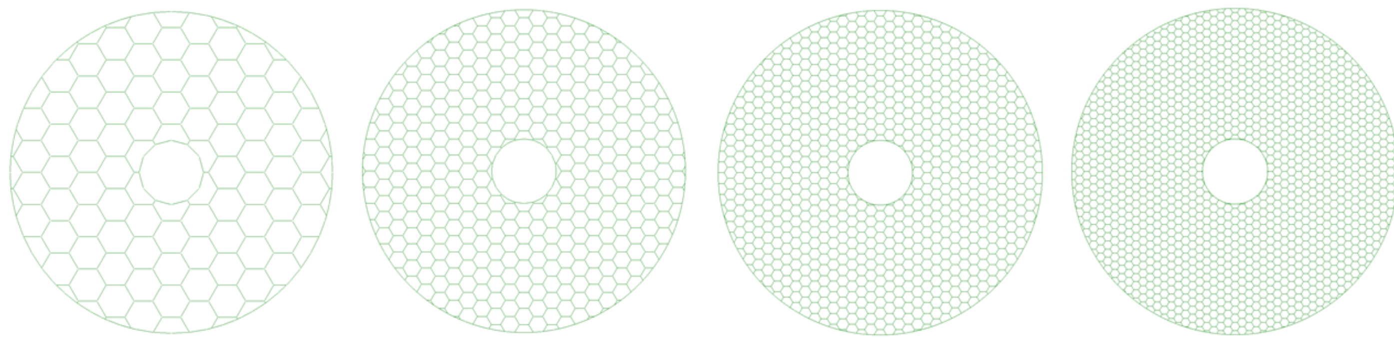
21 supports,
248 psi





100 Hz and 200 Hz Point Designs

- Example of imposing a criteria, such as lowest bending mode of the mirror, which is not difficult for small mirrors to achieve, but impossible for larger mirrors.
- Assumptions, ULE as material, waterjet light-weighted core, frit bonded, limited to current or reasonable future enhancement capabilities of these techniques.

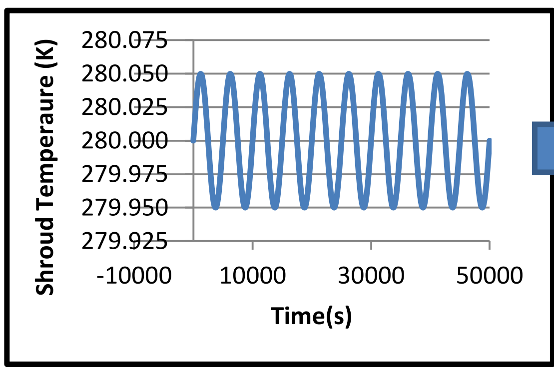


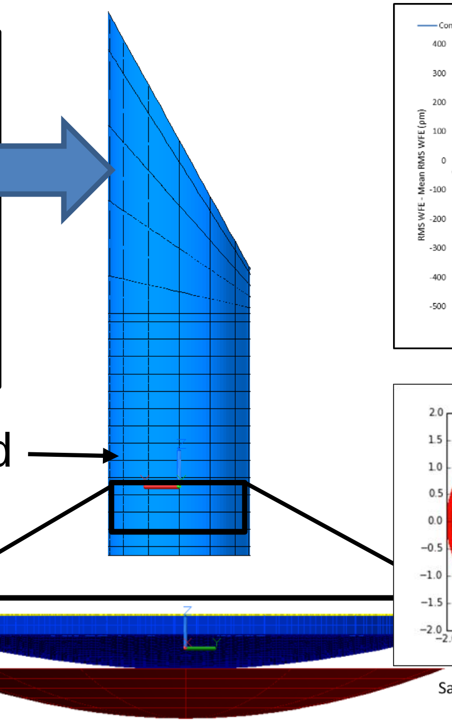
CRITERIA	2 meter		4 meter		6 meter		8 meter	
	kg	hz	kg	hz	kg	hz	kg	hz
100 hertz	88	100	911	106	14908	106	(2)	(2)
200 hertz	130	231	5727	204	(1)	(1)	(2)	(2)

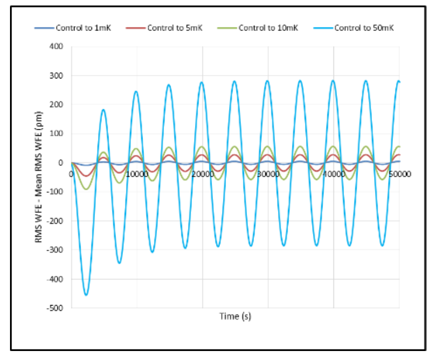
(1) Doubling facesheet thickness (24010 kg) still only increased f=109 hz.
(2) Upper limits of feasible design (32,312 kg) only produced f=66 hz. at 8 meter OD

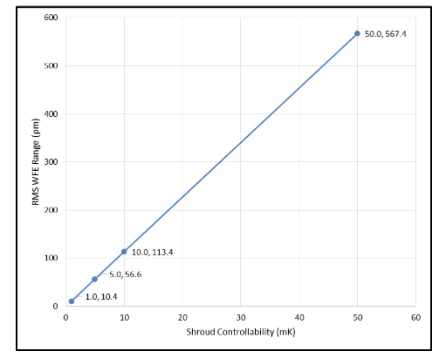
Thermal Stability Study

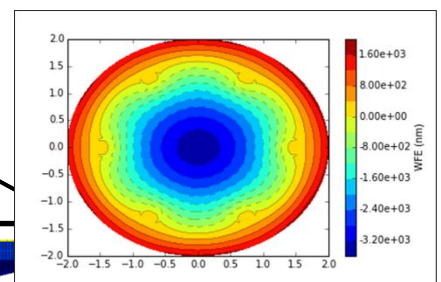
- Understand how primary mirror responds to dynamic external thermal environment.
- Specify how to control telescope thermal environment to keep primary mirror stable to better than 10 pm per 10 minutes



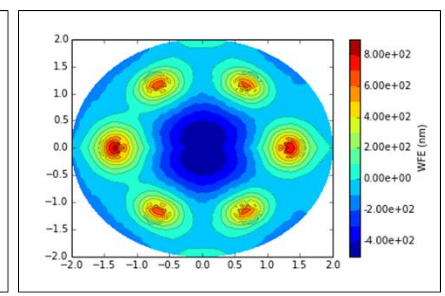








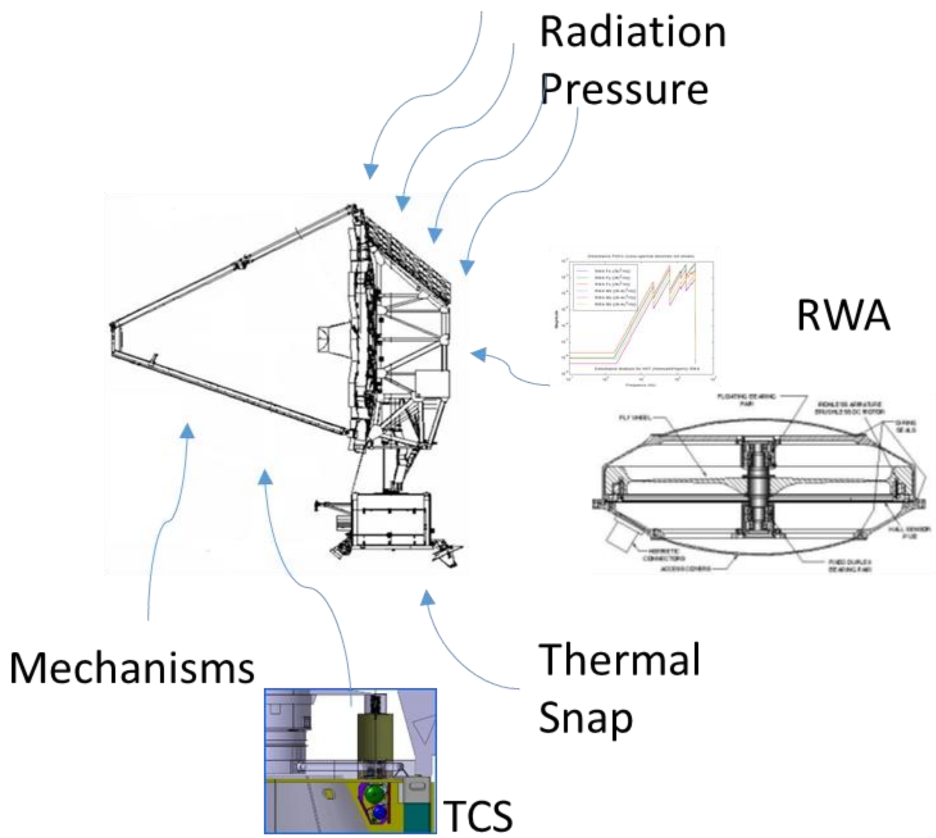
Sample WFE Contour Plot (50mK, 140s Period)

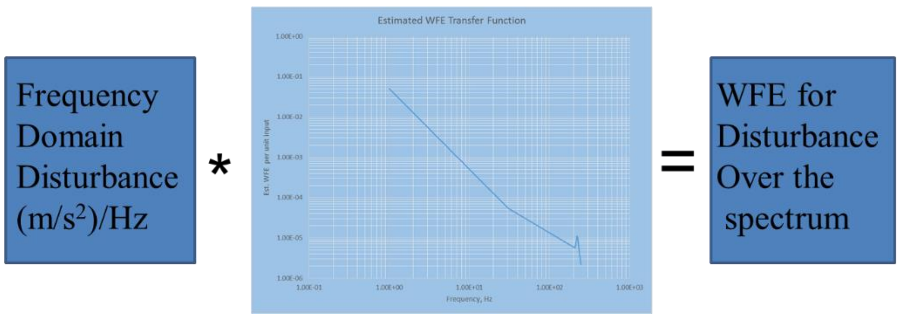


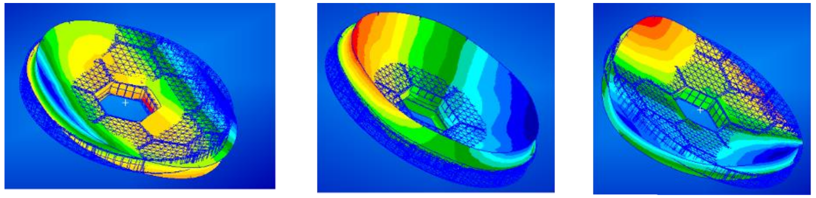
Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)

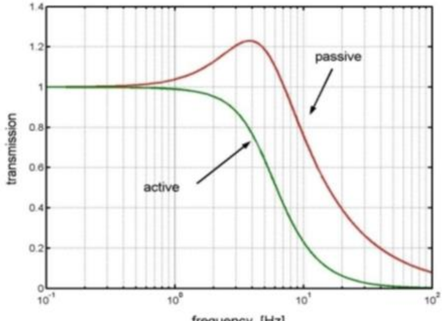
Mechanical Stability Study

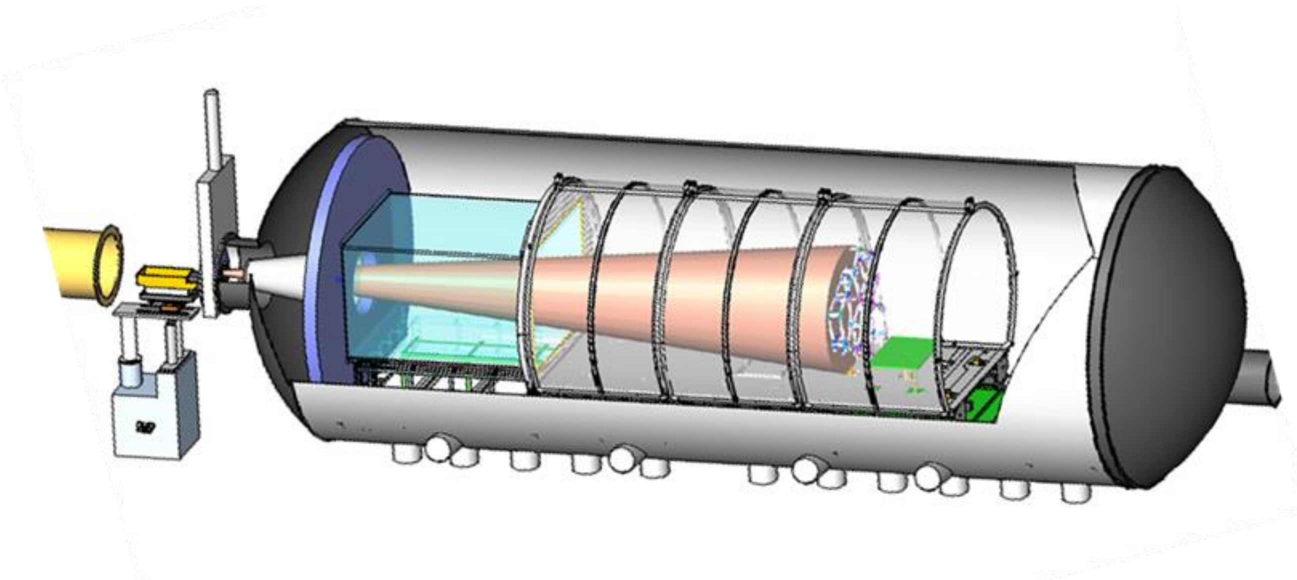
- Understand how primary mirror responds to dynamic external mechanical environment.
- Specify how to control telescope mechanical environment to keep primary mirror stable to better than 10 pm per 10 minutes

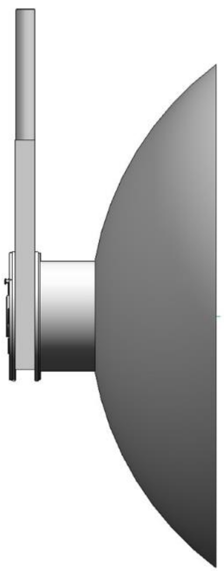


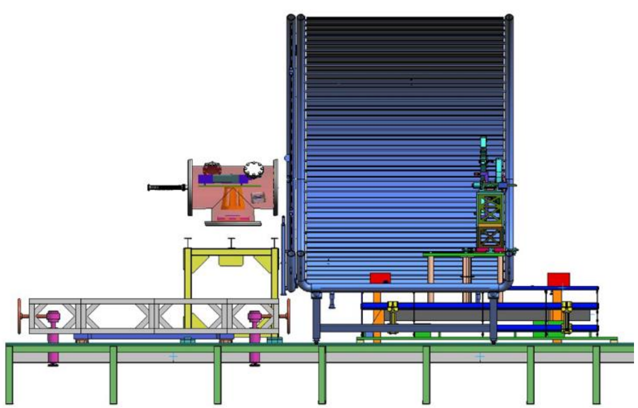


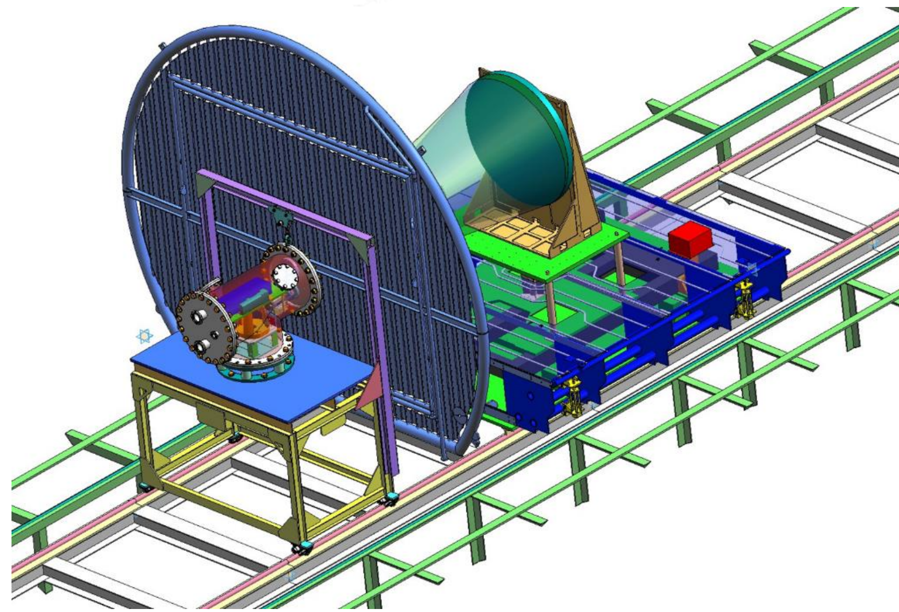




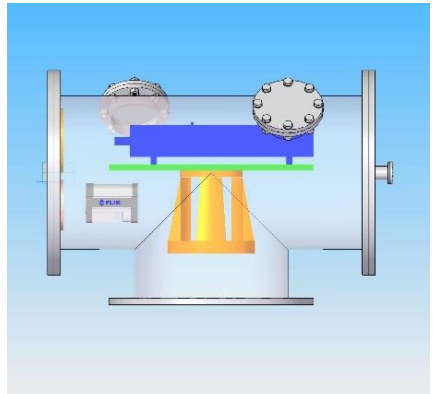


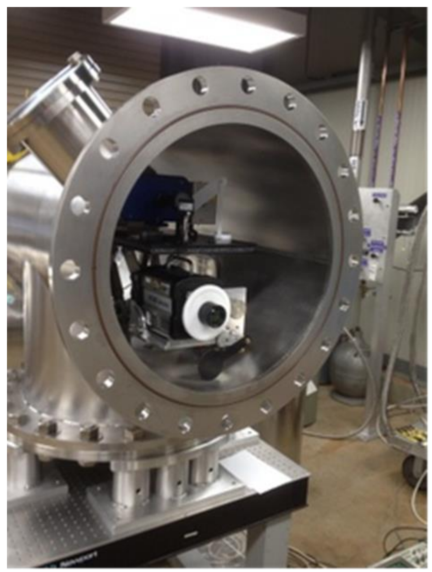






Pressure Tight Enclosure





1. alignment CCD
2. alignment pinhole
3. interferometer
4. ADM
5. IR camera stage
6. hexapod

Segment to Segment Gap Phasing

Gersh-Range, Jessica; William R. Arnold, Sr.; H. Philip Stahl, “Edgewise connectivity: an approach to improving segmented primary mirror performance”, Journal of Astronomical Telescope and Instrument Systems, (2014) DOI: 10.1117/1.JATIS.1.1.014002

Gersh-Range, Jessica; William R. Arnold, Sr.; David Lehner; H. Philip Stahl, “Flux-pinning mechanisms for improving cryogenic segmented mirror performance”, Journal of Astronomical Telescope and Instrument Systems, (2014) DOI: 10.1117/1.JATIS.1.1.014001

Segment to Segment Gap Phasing

Technical Challenge:

- Diffraction limited performance requires ‘co-phased’ segments.
- Segment to Segment motion degrades exoplanet contrast performance.
    - To avoid speckle noise which can interfere with exo-planet observation, Internal coronagraphs require segment to segment dynamic co-phasing error < 10 pm rms between WFSC updates.

Achievement

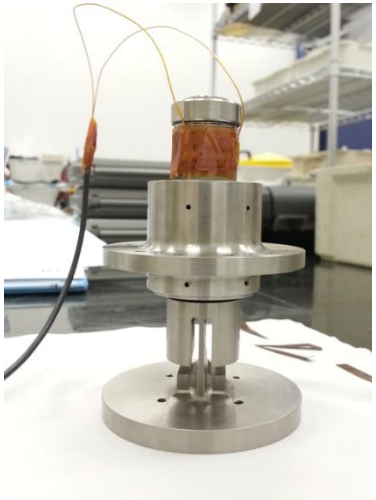
- AMTD developed a model to investigate the effect of edgewise connectivity with dampening to improve dynamic mirror performance.
- AMTD investigated mechanism technology to ‘phase’ segments.
    - Woofer/Tweeter two-stage actuator
    - Flux-Pinning Interface
    - Correlated Magnetic interface

Two-Stage Actuation Mechanism

Demonstrated Fine Rigid Body Actuator (FRBA) at Harris

- Completed assembly and testing of flight traceable FRBA
- Demonstrated compliance with all requirements except resolution
- Demonstrated the ‘fine’ stage of a low mass two stage actuator which could be used co-phase segments
  - Ability to verify actual resolution was limited by test set & electronics design
  - Using improved low noise electronics will enable requirement to be achieved

Property	Performance
Mass	0.313 Kg
Axial stiffness	40.9 N/µm
Test Range	14.1µm
Resolution	6.6 nm (noise limited result) [expected is 0.8 nm]
Accuracy	1.1 µm

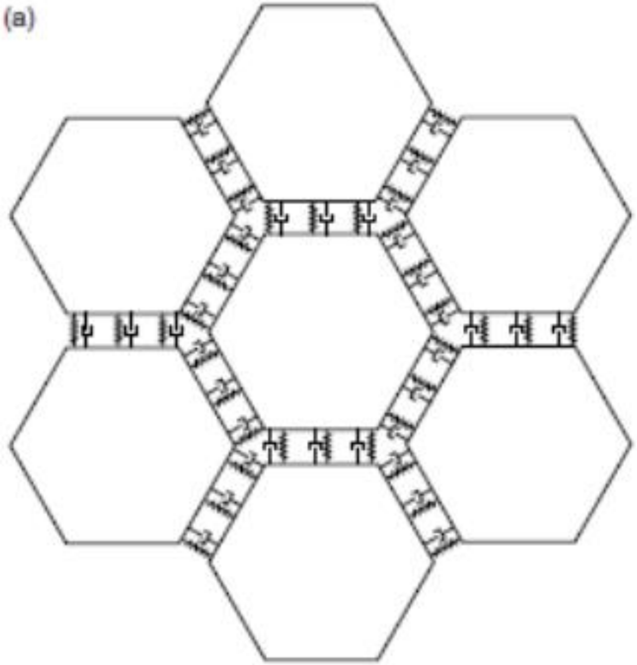


Segment Dynamic Motion

Rapid Random Segment rigid body motion (Piston & Tip/Tilt) reduces dark hole contrast by moving energy from the core into speckles and diffraction spikes.

Connecting segments together at the edges with damped spring interfaces provides potentially significant performance advantages for very large mirrors.

(a)



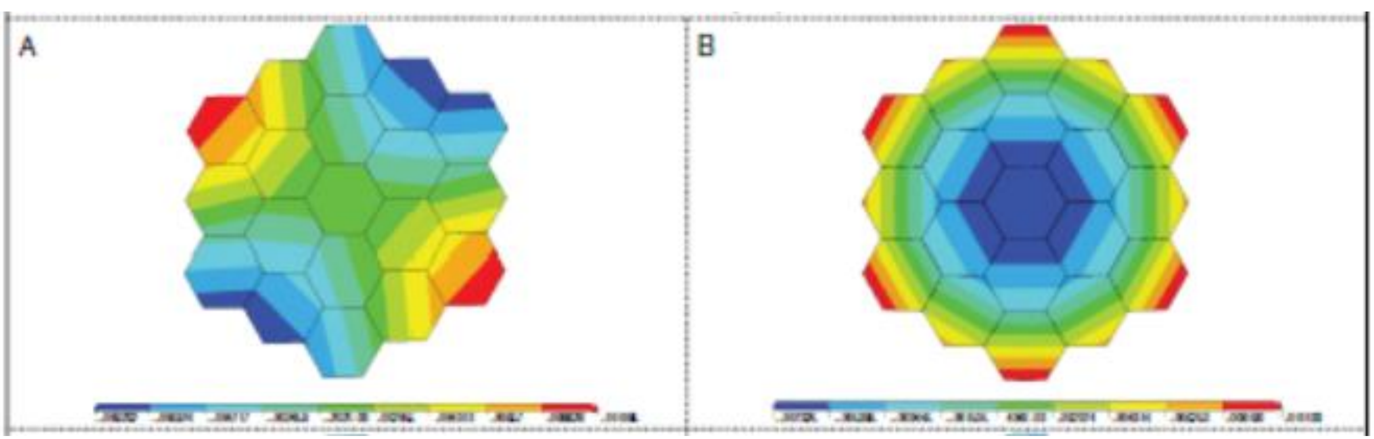
Gersh-Range, Jessica; William R. Arnold, Sr.; H. Philip Stahl, "Edgewise connectivity: an approach to improving segmented primary mirror performance", Journal of Astronomical Telescope and Instrument Systems, (2014) doi: 10.1117/1.JATIS.1.1.014002

Segmented Mirror Dynamic Motion

With no edgewise connectivity, segments behave independently.

With as few as 3 edgewise damped spring interfaces, the segments start to act as a monolith.

Adjusting spring stiffness tunes the assembly's first mode frequency proportional to square root of interface stiffness, but approaches monolithic performance asymptotically.



Gersh-Range, Jessica; William R. Arnold, Sr.; H. Philip Stahl, "Edgewise connectivity: an approach to improving segmented primary mirror performance", Journal of Astronomical Telescope and Instrument Systems, (2014) doi: 10.1117/1.JATIS.1.1.014002

Segmented Mirror Dynamic Motion

By adjusting stiffness & dampening, a segmented mirror stabilizes faster to a impulse than a monolith.

Low to Intermediate Stiffness does not propagate waves.

High Dampening reduces wave amplitude quickly.

More segment rings perform slightly better than fewer.

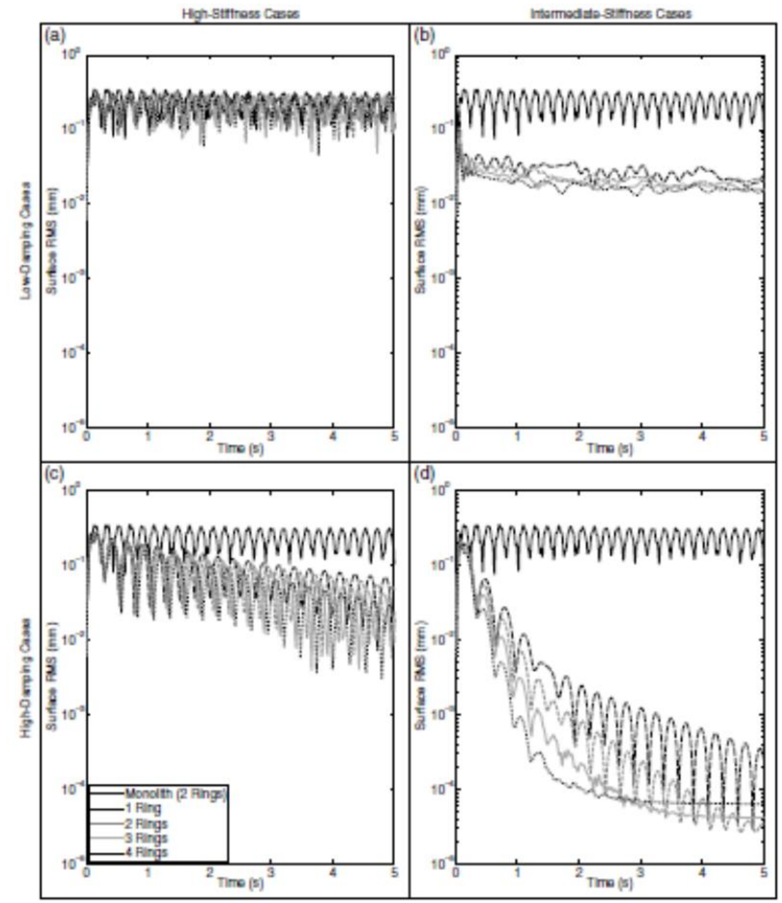


Fig. 9 The effects of ring number on the impulse response for various mechanism cases (a-d).

Gersh-Range, Jessica; William R. Arnold, Sr.; H. Philip Stahl, "Edgewise connectivity: an approach to improving segmented primary mirror performance", Journal of Astronomical Telescope and Instrument Systems, (2014) doi: 10.1117/1.JATIS.1.1.014002

Conclusions

AMTD uses a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.

Assembled outstanding team from academia, industry & government; experts in science & space telescope engineering.

Derived engineering specifications from science measurement needs & implementation constraints.

Maturing 6 critical technologies required to enable 4 to 8 meter UVOIR space telescope mirror assemblies for both general astrophysics & ultra-high contrast exoplanet imaging.

AMTD achieving all its goals & accomplishing all its milestones